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Numerical study of squeaking suppresses for ceramic-on-ceramic hip endoprosthesis

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ABSTRACT

A finite element model of a ceramic hip endoprosthesis system is established with ABAQUS 6.7 and the motion stability of the model is studied using the complex eigenvalue method. Numerical results reveal that a torsional vibration and a flexural vibration of the femoral component are responsible for squeaking. Increasing Young's modulus of the stem, adding CoCrMo alloy as well as 316 L stainless steel in the stem and adding a whole damping layer of UHMWPE to the acetabular component can improve the vibrant stability of the system, then, suppress the squeaking.

1. Introduction

Ceramic-on-ceramic(COC) bearings can eliminate polyethylene wear and improve the lifespan of the implants; moreover the third and the fourth generations of alumina ceramic have demonstrated excellent tribological properties, high wear resistance and good biocompatibility [1,2]. Those advantages make ceramic hip prosthesis be widely used in total hip arthroplasty (THA), especially for young patients. However, the occurrence of squeaking in ceramic-on-ceramic THA has been claimed recently as a potential worrisome problem.

Charnley [3] observed that the presence of frictional conditions could lead to squeaking in hip replacement patients as early as 1979. The prevalence of squeaking ceramic bearings recently reported in published articles ranged from under 1% to nearly 8% [4–7], some were even more than 10% [8]. Research is therefore being conducted in the context of a global project to identify the causes of squeaking and the main factors leading to its development. The reported etiologies of squeaking implicate patient factors such as avoirdupois and exercise [4], surgical implantation factors such as microseparation, malposition and mismatch [9–12], factors with respect to the design of prosthesis itself such as improper design of metal cup [13] and factors of friction-induced vibration of hip endoprosthesis systems [14,15]. Actually, any sound in the audible range results from the vibration. Therefore, studying squeaking on ceramic hips is transferred to analyzing the vibration characteristics of the ceramic hip endoprosthesis system. Weiss et al. [14] and Walter et al. [15] have indicated that high friction coefficient resulting from lubrication disruption between ceramic bearings can induce unstable vibration of a ceramic hip prosthesis system, therefore lead to squeaking. Although researchers have recognized that friction-induced vibration is probably responsible for squeaking, there is not a realistic method for suppressing squeaking generation effectively up to now.

Most recently, our research group is engaged in the study of squeaking in ceramic hips using the numerical method on the base of the theory of friction vibration [16]. After optimizing the size of the prothesis and establishing its boundary conditions closer to the conditions in vivo, the authors propose some available methods to suppress the squeaking of a ceramic hip endoprothesis system in the present paper. It is significant for solving the problem of squeaking.

2. Methodology and numerical model

2.1. Complex eigenvalue method

Automotive disk brake squeal is a typical friction sound in our daily life. Liles [17] used the complex eigenvalue method for studying the mechanism of automotive disk brake squeal as early as 1989. The complex eigenvalue analysis can obtain all unstable frequencies for one operating condition in one computational cycle. The analysis can be repeated for all valid operating conditions (such as for all variations of parameters), and the result can be given as a mode distribution over the parameter-range of

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interest. The complex eigenvalue analysis has been proved to be a useful tool for studying the instability of braking systems and revealing the mechanism of friction-induced vibration [18–22]. The complex eigenvalue method can find a large number of unstable modes, but not all unstable modes can be observed in experimental tests. A dynamic transient analysis is another method available to study squeal. This method can find several unstable modes, which are included in the results obtained by the complex eigenvalue method. However, the dynamic transient analysis is computationally expensive [23]. Similar to brake squeal, squeaking of ceramic hips may be radiated by friction-induced vibration of a ceramic hip endoprosthesis system. Weiss and Morlock et al. [24] appear to be the first researchers who tried to incorporate the complex eigenvalue analysis with biotribology on the purpose of solving squeaking problems and proved that this method was feasible.

The aim of the complex eigenvalue analysis is to determine both eigenfrequencies and eigenvectors of a friction system together with the corresponding damping factors resulting from the non-conservativeness of the system that is subjected to frictional contact. Nowadays, the method of Yuan [25] is popular for the analysis of disk brake squeal. Here, the methodology of the complex eigenvalue analysis is introduced briefly. The motion equations of an elastic system are generally written as follows:

$$M\ddot{x}+C\dot{x}+Kx=0 \tag{1}$$

where M is the mass matrix. C is the damping matrix, which includes friction-induced contributions. K is the stiffness matrix, which is unsymmetric due to friction. The corresponding characteristic equations can be written as

$$(\lambda^2 M+\lambda C+K)\Phi=0 \tag{2}$$

where λ is an eigenvalue and Φ is the corresponding eigenvector. Both eigenvalues and eigenvectors may be complex. In order to solve the complex eigenproblem, both the damping matrix and the unsymmetric contributions of K are neglected. This yields

$$(-\omega^2 M+K)\Phi=0 \tag{3}$$

where ω is a eigenfrequency of the system. Then this symmetric eigenvalue problem is solved to find the projection subspace. The N eigenvectors obtained from the symmetric eigenvalue problem are expressed in a matrix as $[\phi_1,\ldots,\phi_n]$. Next, the baseline matrices are projected onto the subspace of N eigenvectors:

$$\begin{aligned} M^* &= [\phi_1,\ldots,\phi_n]^T M[\phi_1,\ldots,\phi_n] \\ C^* &= [\phi_1,\ldots,\phi_n]^T C[\phi_1,\ldots,\phi_n] \\ K^* &= [\phi_1,\ldots,\phi_n]^T K[\phi_1,\ldots,\phi_n] \end{aligned} \tag{4}$$

Then, the complex eigenproblems are simplified as follows:

$$(\lambda^2 M^*+\lambda C^*+K^*)\Phi^*=0 \tag{5}$$

Finally, the complex eigenvectors of the baseline system can be obtained by

$$\phi^k=[\phi_1,\ldots,\phi_n]^T\phi^{*k} \tag{6}$$

The general solution of Eq. (5) is as below:

$$x(t)=\sum\{\phi_i\}\exp(\lambda_i t)=\sum\{\phi_i\}\exp(\alpha_i+j\omega_i)t \tag{7}$$

where $\{\phi_i\}$ is an eigenvector of Eq. (5). $\lambda_i=\alpha_i+j\omega_i$ is an eigenvalue of Eq. (5), where α is the real part of λ, denoted as Re(λ), which indicates the stability of the system and ω is the imaginary part of λ, denoted as Im(ω), which indicates the mode frequency. When the system is unstable, α becomes positive and squeal noise occurs.The damping ratio is defined as

$$\zeta=-\alpha/(\pi|\omega|) \tag{8}$$

With the increase of friction, the stability of the system will change. There is a critical friction coefficient, above which the system becomes unstable. In the present study, if the damping ratio is negative, the system becomes unstable and has a tendency to radiate squeaking, vice versa.

In the present paper, ABAQUS's complex eigenvalue analysis capability is applied to study the vibrant stability of the ceramic hip endoprosthesis system. The main procedures for applying ABAQUS to perform the complex eigenvalue analysis of ceramic hip endoprosthesis are given as follows:

(1) Nonlinear static analysis of the ceramic hip endoprosthesis system for applying concentrated forces.
(2) Nonlinear static analysis to impose rotation speed on the femoral components.
(3) Normal mode analysis to extract natural frequencies without friction coupling.
(4) Complex eigenvalue analysis that incorporates the effect of friction coupling.

2.2. Numerical model

Fig. 1 shows schematically a ceramic hip endoprosthesis system, which includes a metallic shell, a ceramic liner, a ceramic ball and a metallic stem (Fig. 1a). The metal parts including a shell and a stem were embedded in the simulative bone as shown in Fig. 1c. One anear acetabular component is denoted as bone A, another anear femoral component is denoted as bone F. The size of prosthetic components and the parameters of prosthetic materials in the present model were close to the real artificial joint, in which the diameter of ceramic head was 28 mm, the outside diameter of ceramic liner was 44 mm. The shell and the stem were made of Ti6A14V alloy [26]. The acetabulum and the femoral head were made of a composite ceramic [2]. Two simulative bones were made from a special material [24]. All materials were assumed to be homogeneous, isotropic and linear elastic. The important material parameters required for the FEM analysis are listed in Table 1. The 8-node hexahedral element (C3D8I) was selected to mesh the model as shown in Fig. 1b. In particular, finer meshing of contact surfaces between the liner and the ball was made in order to obtain a better contact analysis result. The contact between the liner and the ball was modeled using a tangential penalty formulation with finite sliding algorithm and a Coulomb-type friction with a constant coefficient of friction μ. The other contact junctions including bone A/shell, shell/liner, ball/stem and stem/bone F have little relative motion when the ceramic hip endoprosthesis system works. Therefore, all of them were defined as tie constraints in the FE model.

2.3. Load and boundary conditions

The load and boundary conditions of FEA model are shown in Fig. 2. Some relevant studies have indicated that hip joint resultant force is 2–3 times of the weight of human body during normal gaiting [27]. Assuming the weight of a person to be 60 kg, the hip joint resultant force can be set as 1500 N, which is applied at the end of the stem in the direction of Y-axis as shown in Fig. 2. The boundary conditions of the actual hip prostheses are too complicated to completely simulate in the finite element analysis. Some constraint mechanisms of actual hip prostheses are also hard to identify. In the present work, a heuristic method of boundary conditions is applied. In the heuristic method, assuming boundary constraints as reasonable as possible are imposed on the hip prosthesis system. Based on these assuming boundary constraints, excited-vibration characteristics of the hip prosthesis

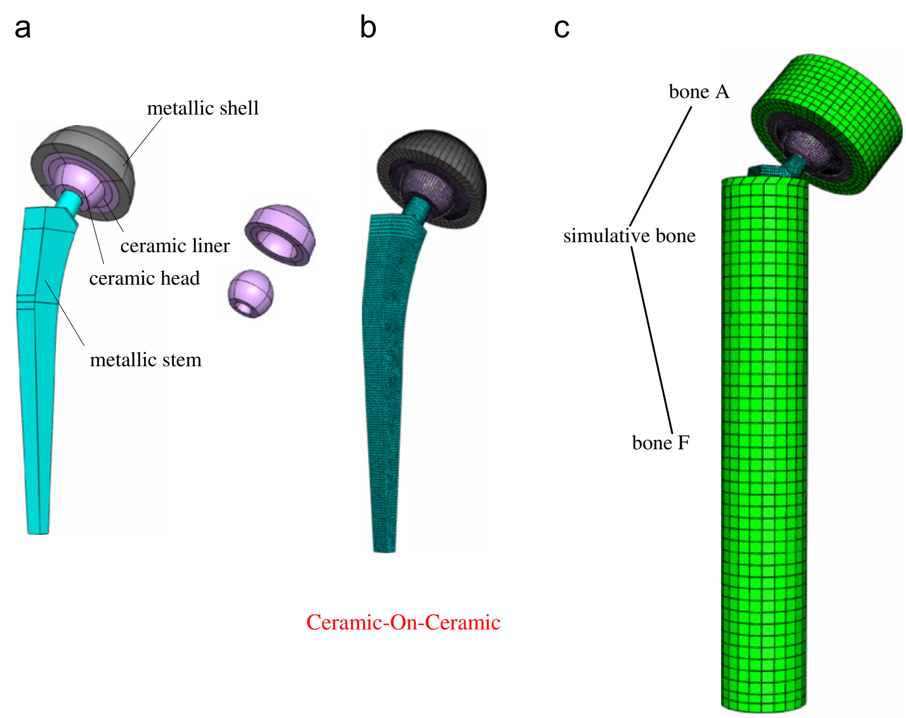

Fig. 1. FE model of a ceramic hip endoprosthesis system: (a) components of the prosthesis, (b) FE model with C3D8I and (c) metallic shell and metallic stem being embedded in the simulative bone.

Table 1
Parameters of prosthetic materials.

Materials	Density (kg/m^3)	Young's modulus (N/m^2)	Poisson ratio
Ti6Al4V	4500	1.10×10^{11}	0.3
Ceramic	4370	3.58×10^{11}	0.23
Simulative bone	1932	2.0×10^{10}	0.3

system are obtained. If the excited-vibration characteristics are approximate to those of the hip prosthesis system measured in field tests, these assuming boundary conditions to be valid. In the present study, in order to produce stable friction between the interface of the liner and the ball, bone A is supposed to be fixed and the edge of the bone F is fixed to assure the original placement of the system. Then the femoral component including a femoral head, a stem and a bone F is imposed a rotational motion of 1 rad/s around the *Y*-axis to produce stable friction.

3. Results

3.1. Vibrant stability analysis of the baseline ceramic hip endoprosthesis system

If the fluid film lubrication between ceramic bearings works well, the friction coefficients of ceramic bearings are only 0.0018–0.0032 [28]. However, when loss of fluid film lubrication occurs with hard-on-hard bearings, the friction coefficient for alumina ceramic-on-ceramic bearings can be as high as 0.53 [29]. The vibrant stability of the system is therefore studied under different friction coefficients from 0 to 0.5. Fig. 3 shows the unstable mode frequency distribution and the corresponding unstable mode shapes of the baseline ceramic hip endoprosthesis system. Unstable mode frequencies are distributed in three frequency bands of 1843–2050 Hz, around 3300 Hz and 4700–4970 Hz. The measured squeaking frequencies from two in vivo acoustic analysis of COC hips were reported to be 1546 Hz,

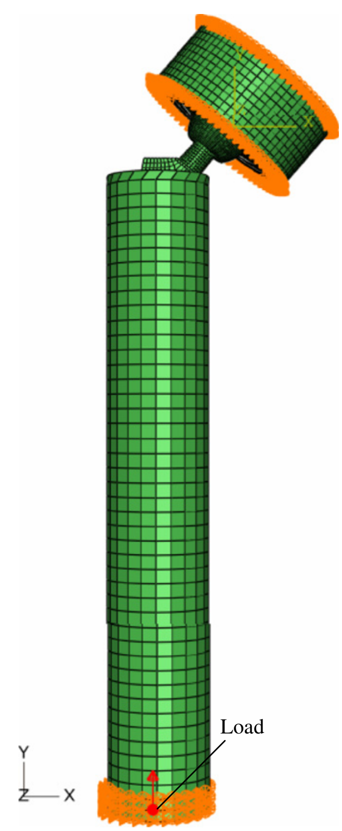

Fig. 2. FEA model of a ceramic hip prosthesis system with loading and boundary condition.

3046 Hz and 4593 Hz [15]; another measured squeaking frequencies were 1540 Hz, 3090 Hz and 4620 Hz [30]. There is a base frequency and some higher harmonics in these two experimental results, which are calculated by Power Spectrum Density(PSD). In the present study,

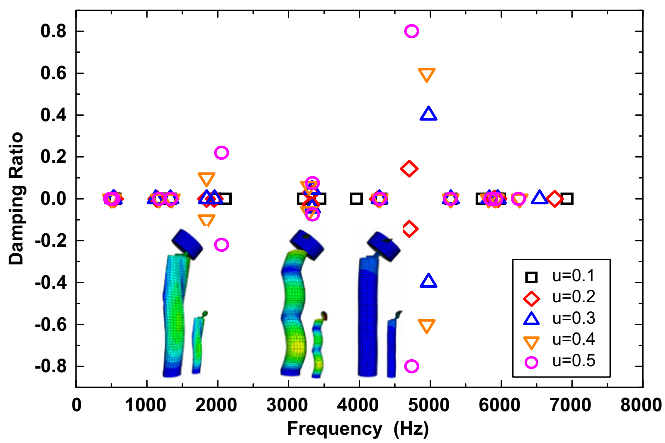

Fig. 3. Unstable mode frequency distribution and the corresponding unstable mode shapes of the baseline ceramic hip endoprosthesis system.

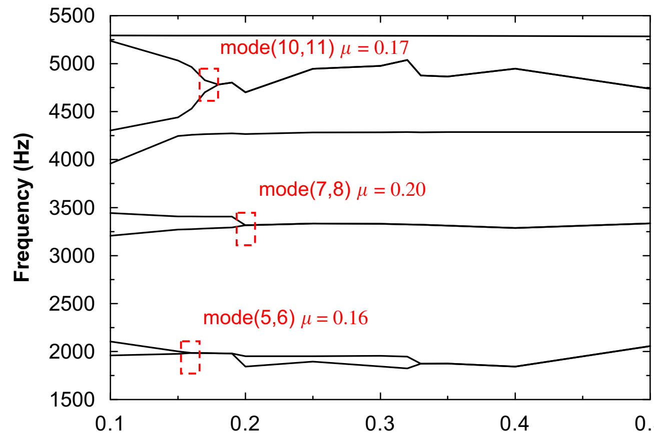

Fig. 4. Mode coupling of the baseline ceramic hip endoprosthesis system.

the squeaking frequencies, which are calculated by the complex eigenvalue method are found to be approximate to the base frequencies measured in field tests. Therefore, the FEA model established in the paper is useful and the complex eigenvalue method is reliable.

The corresponding unstable mode shapes of the system are a torsional vibration of the femoral component, a flexural vibration of the femoral component and a large deformation of the femoral head, while the acetabular component has little deformation under friction coupling. Generally speaking, unstable modes at lower frequencies are more likely to be induced by friction in a real condition [22]. Compared with the unstable modes at 4700–4970 Hz, unstable modes at 3300 Hz and especially at 1843–2050 Hz are more likely to be induced by friction. Therefore, the torsional vibration of the femoral component at 1843–2050 Hz and the flexural vibration of the femoral component at 3300 Hz are most likely to be responsible for squeaking. Then, improving the capacity of the ceramic hip prosthesis system to resist the torsional vibration and the flexural vibration of the femoral component can improve the vibrant stability of the system, therefore, suppress the squeaking.

With the increase of the friction coefficient, oscillation frequencies of two adjacent structural modes of a system will change and approach to each other. When the friction coefficient increases to the critical value, these two modes completely coalesce. In this case, there is a pair of stable and unstable modes. The critical friction coefficient, above which the unstable vibration of the ceramic hip endoprosthesis system occurs, can represent the instability tendency of the system to some extent. Fig. 4 shows the mode coupling initiation of the baseline system and the corresponding critical friction coefficients. Since unstable mode frequencies of the baseline system range from 1843 Hz to 4970 Hz, the frequencies from 1500 Hz to 5500 Hz are used to analyze the mode coupling, which are denoted by mode 5 to mode 12. It can be seen that with increasing friction coefficient, the frequencies of modes 5 and 6 approach to each other. When $\mu=0.16$, these two modes completely coalesce at 1986 Hz, denoted as mode(5, 6). The corresponding unstable mode shape is a torsional vibration of the femoral component. Similarly, When $\mu=0.17$ modes 10 and 11 completely coalesce at 4895 Hz, denoted as mode(10, 11). When $\mu=0.20$ modes 7 and 8 completely coalesce at 3300 Hz, denoted as mode(7, 8). The corresponding unstable mode shape is a flexural vibration of the femoral component. It has been mentioned above that the torsional vibration of the femoral component at 1843–2050 Hz and the flexural vibration of the femoral component at 3300 Hz are most likely to be responsible for squeaking. Therefore, increasing the critical friction coefficients at mode(5, 6) and mode(7, 8), especially at mode(5, 6) to those values, which is difficult to be reached when ceramic bearings work can improve the capacity of the system to resist a torsional vibration and a flexural vibration of the femoral component, so as to suppress squeaking. So, the critical friction coefficients of mode(5, 6) and mode(7, 8) of the system are proposed to judge the stability of COC hip endoprosthesis system.

3.2. *Influence of the stem parameters on the vibrant stability of the ceramic hip endoprosthesis system*

3.2.1. *Young's modulus of the stem*

Since the torsional vibration and the flexural vibration of the femoral component are responsible for squeaking, the stem included in the femoral component may have a great influence on the squeaking generation. Hothan et al. [31] and Restrepo et al. [32] are recently engaged in the study of the relationship between the stem and the squeaking. Restrepo et al. [32] indicated that the prevalence of squeaking was seven times higher for patients who received the titanium–molybdenum–zirconium–iron-alloy stems than that for those who received the titanium–aluminum–vanadium-alloy stems (the one in the present model).

Young's modulus of titanium–molybdenum–zirconium–iron material is 30–40% less than that of the titanium–aluminum–vanadium-alloy stem, the titanium–molybdenum–zirconium–iron material is more flexible than the titanium–aluminum–vanadium-alloy stem even with the same geometry. In the present study, $E_0=1.1\times10^{11}$ N/m stands for the baseline of Young's modulus of the stem; the adjustive Young's moduli E are assumed to be $0.6E_0$, $0.7E_0$, $1.0E_0$, $1.1E_0$, $1.2E_0$ and $1.3E_0$. Setting Young's modulus of $0.6E_0$ and $0.7E_0$ is to verify Restrepo's research results. It can also reveal the influence of Young's modulus of the stem on the stability of the COC prosthesis system. Since squeaking is easier to occur when decreasing Young's modulus of the stem, increasing Young's modulus of the stem can improve squeaking stability and suppress squeaking. Therefore, Young's modulus E is assumed to be $1.1E_0$, $1.2E_0$ and $1.3E_0$. Fig. 5 shows the unstable mode frequency distribution of the ceramic hip endoprosthesis system for different Young's modulus of the stem under friction coupling. The friction coefficient is the same in each subfigure of Fig. 5, while Young's modulus of the stem is different. Therefore, the damping ratio is different, which is used to reveal the influence of the stiffness of the stem on the stability of the system. It can be seen that when the friction coefficient is 0.05 there is an unstable mode of about 499 Hz when Young's modulus is $0.6E_0$ as shown in Fig. 5a. When the friction coefficient

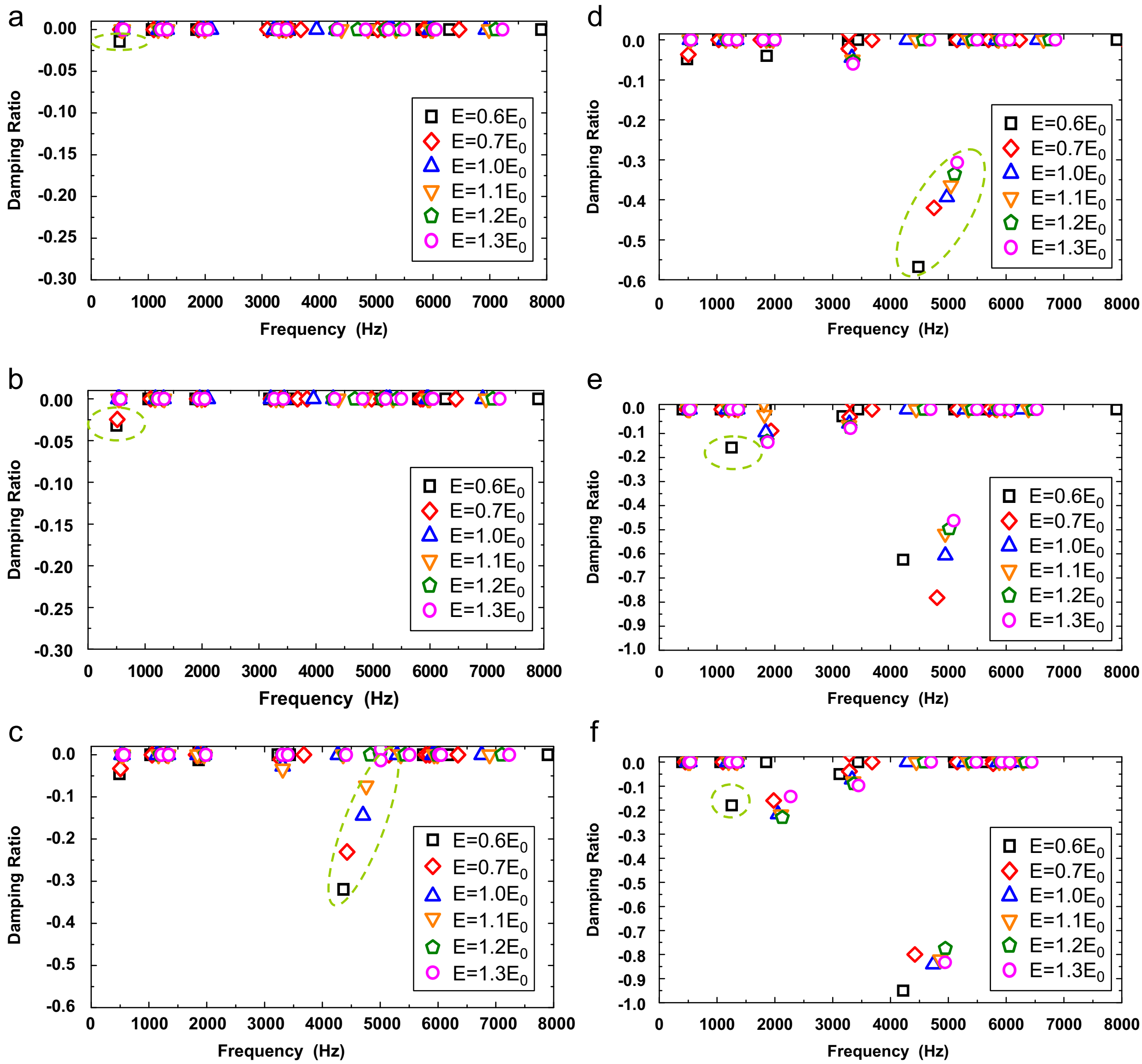

Fig. 5. Unstable mode frequency distribution of the ceramic hip endoprosthesis system for different Young's modulus of the stem under friction coupling. (a) μ=0.05, (b) μ=0.1, (c) μ=0.2, (d) μ=0.3, (e) μ=0.4 and (f) μ=0.5.

increases to 0.1 there is also an unstable mode of about 499 Hz when Young's modulus is $0.7E_0$ as shown in Fig. 5b. While there is no unstable mode when Young's modulus ranges from $1.0E_0$ to $1.3E_0$. That result shows that the critical friction coefficient of unstable mode occurrence decreases with decreasing stiffness of the stem. In the case, the system is easier to radiate noises and squeaking. The present result is consistent with Restrepo's conclusion [32]. When the friction coefficient increases to 0.2 and 0.3, there are still the unstable mode at about 499 Hz and some high-frequency unstable modes when Young's modulus are $0.6E_0$ and $0.7E_0$ as shown in Fig. 5c and d. For Young's modulus range from $1.0E_0$ to $1.3E_0$, unstable mode frequency distributions are similar while the absolute value of the negative damping ratio becomes lower with increasing Young's modulus. The results from Fig. 5c and d indicate that increasing the stiffness of the stem, the vibrant stability of the ceramic hip endoprosthesis system will be improved to some extent. When the friction coefficient increases to 0.4 and 0.5, there is an unstable mode of about 1300 Hz at a Young's modulus of $0.6E_0$ as shown in Fig. 5e and f. This unstable mode is very close to the fundamental squeaking frequency of 1546 Hz in vivo [15]. As a result, the system becomes more unstable with decreasing the stiffness of the stem, then, easily radiate noises and squeaking. In order to better understand the effect of the stiffness of stem on the stability of the system, the mode coupling of the system when Young's modulus is $1.3E_0$ has been studied in detail as follows.

Fig. 6 shows the mode coupling of the system when Young's modulus of the stem is $1.3E_0$. Compared with the critical friction coefficients of the baseline system as shown in Fig. 4, it is found that the critical friction coefficients of mode(5, 6), mode(7, 8) and mode(10, 11) increase from 0.16 to 0.17, from 0.2 to 0.23 and from 0.17 to 0.18, respectively. The result indicates that increasing the stiffness of stem can improve the vibrant stability of the system and suppress squeaking to some extent. In contrast, decreasing the stiffness of the stem can easily result in the torsional and flexural coupling vibration of the femoral component, which leads to noise and squeaking of the system.

3.2.2. *Structure modification of the stem*

The authors' work shows that adding hard alloy such as CoCrMo alloy and 316 L stainless steel (316 L SS) in the stem can improve the capacity of the ceramic hip endoprosthesis system to resist the torsional vibration and the flexural vibration of the femoral component, therefore can suppress squeaking. CoCrMo alloy and 316 L SS are two common metallic prosthetic materials used in arthroplasty. The parameters of these two materials are as shown in Table 2. There are three schemes for adding hard alloy in the stem as shown in Fig. 7, in which hard alloys are added in the center of the stem, in two sides of the stem and in the transverse levels of the stem, respectively.

Fig. 8 shows the unstable mode frequency distributions of the systems after adding CoCrMo alloy in the stem. It can be seen that

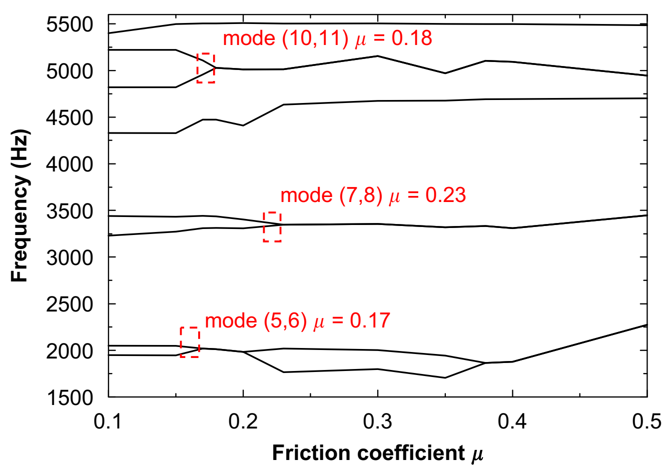

Fig. 6. Mode coupling of the ceramic hip endoprosthesis system when $E=1.3E_0$.

Table 2
Parameters of the hard alloy.

Materials	Density (kg/m^3)	Young's modulus (N/m^2)	Poisson ratio
CoCrMo	8300	2.2×10^{11}	0.3
316 L SS	7900	2.0×10^{11}	0.3

all of the unstable mode frequencies are close to those associated with the baseline system as shown in Fig. 3. Compared with unstable modes of the baseline system, however, it is found that there is no unstable mode at about 1900 Hz when the friction coefficient is 0.4 after adding CoCrMo alloy in the stem. Only when the friction coefficient arrives at 0.5, is there an unstable mode at about 1900 Hz as shown in the broken line in Fig. 8. That is to say, adding CoCrMo alloy in the stem can increase the critical friction coefficient of mode(5, 6), therefore can improve squeaking propensity of the ceramic hip endoprosthesis system. In order to have a better understanding of the vibrant stability improvement of the system, the mode coupling of the system after adding CoCrMo alloy has been studied as follows.

Fig. 9 shows the mode coupling of the ceramic hip endoprosthesis system after adding CoCrMo alloy in the stem. When CoCrMo alloy is added in the center of the stem, the critical friction coefficients of mode(5, 6) and mode(7, 8) increase from 0.16 to 0.43 and from 0.2 to 0.23, respectively, as shown in Fig. 9a. The critical friction coefficient of mode(5, 6) is close to three times of the critical friction coefficient associated with the baseline system. It indicates that the vibrant stability of the ceramic hip endoprosthesis system is improved to a great extent after adding CoCrMo alloy in the center of the stem. After adding CoCrMo alloy in two sides of the stem, the critical friction coefficient of mode(5, 6) increases from 0.16 to 0.43 as shown in Fig. 9b. The vibrant stability of the system is improved as well. When adding CoCrMo alloy in the transverse levels of the stem, the critical friction coefficient of mode(5, 6) increases from 0.16 to 0.41, while the critical friction coefficient of mode(7, 8) decreases from 0.2 to 0.18 as shown in Fig. 9c. Therefore, adding CoCrMo alloy in the transverse levels of the stem cannot improve well the vibrant stability of the system. To sum up, adding CoCrMo alloy in two sides of the stem and especially adding CoCrMo alloy in the center of the stem can improve the vibrant stability of system and suppress squeaking.

Fig. 10 shows the mode coupling of the system after adding 316 L SS in the center of the stem. The critical friction coefficient of mode(5, 6) increases from 0.16 to 0.43, therefore the vibrant stability of the system is improved well. Compared with the result in Fig. 9a, it is found that the critical friction coefficient of mode(5, 6) is similar, but the critical friction coefficients of mode(7, 8) decreases

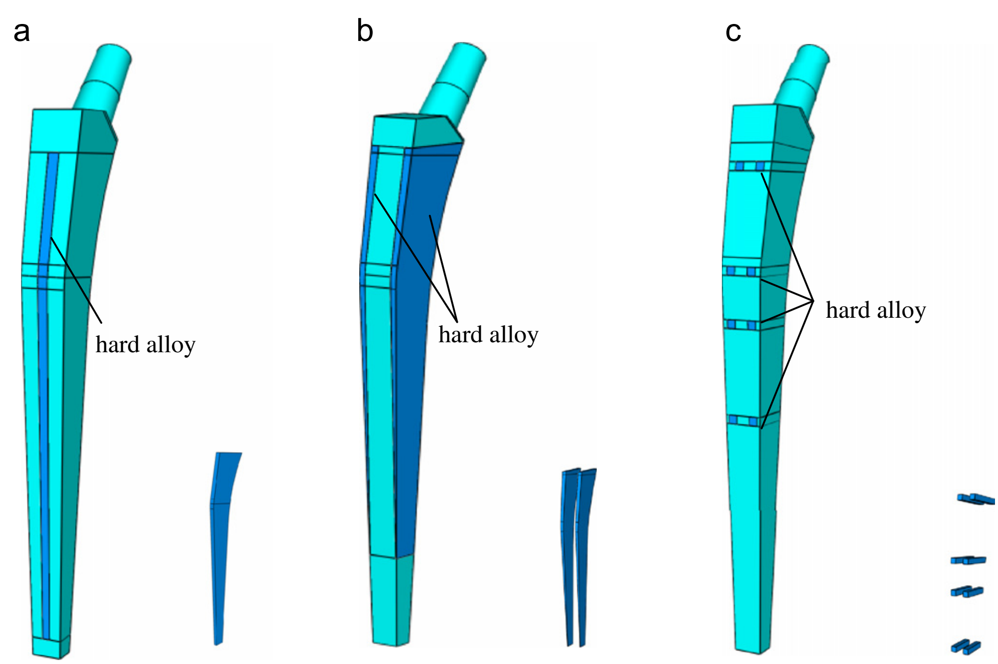

Fig. 7. Three schemes for structure modification of the stem: (a) center addition, (b) side addition and (c) transverse addition.

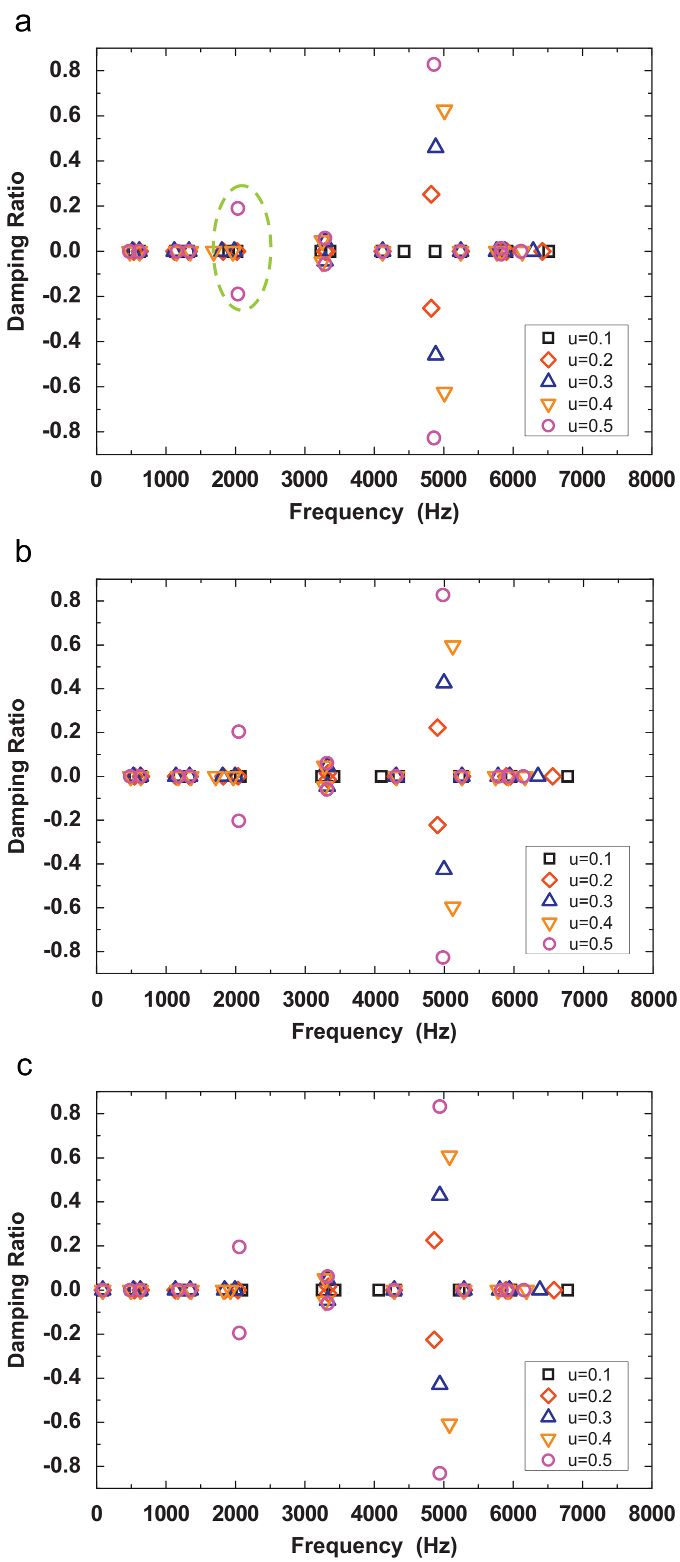

Fig. 8. Unstable mode frequency distribution of the ceramic hip endoprosthesis system after adding CoCrMo alloy in the stem: (a) center addition, (b) side addition and (c) transverse addition.

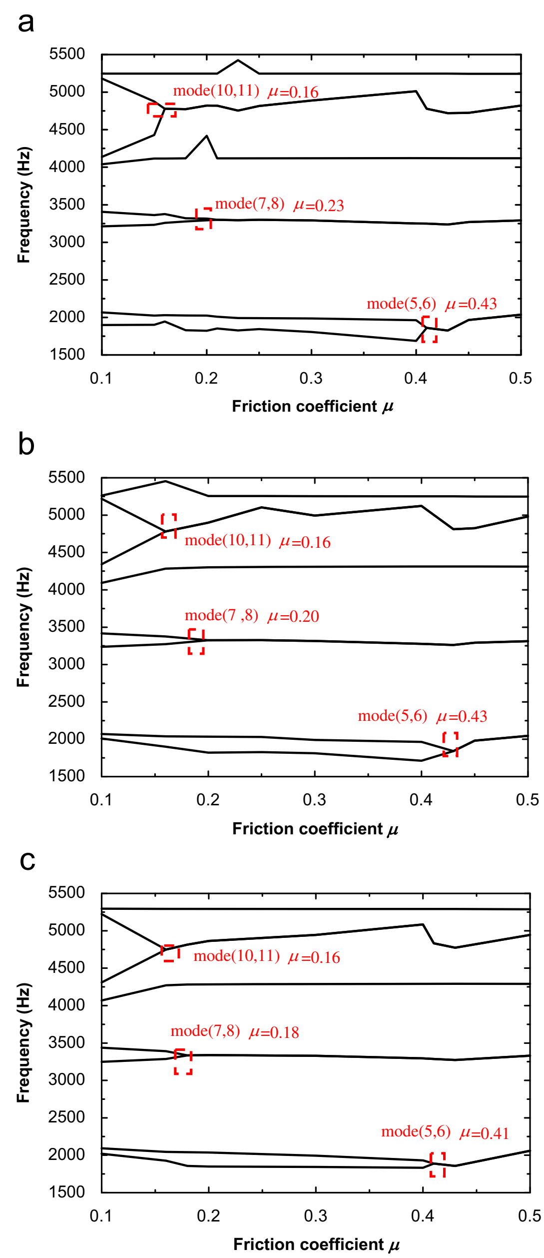

Fig. 9. Mode coupling of the ceramic hip endoprosthesis system after adding CoCrMo alloy in the stem. (a) Mode coupling of the system after adding CoCrMo alloy in the center of the stem, (b) mode coupling of the system after adding CoCrMo alloy in two sides of the stem and (c) mode coupling of the system after adding CoCrMo alloy in the transverse levels of the stem.

from 0.23 to 0.2. It is because the density and Young' modulus of CoCrMo alloy are larger than these of 316 L SS. Therefore, adding CoCrMo alloy in the center of the stem is the best way to suppress squeaking since the critical friction coefficients of mode(5, 6) and mode(7, 8) increase from 0.16 to 0.43 and from 0.2 to 0.23, respectively.

3.3. Influence of damping on the vibrant stability of the ceramic hip endoprosthesis system

Damping serves to control the steady state resonant response and to attenuate traveling waves in the structure. Viscoelastic damping materials are wildly used in control of noise in automobiles [33]. Similarly, if damping is added in the COC prosthesis system, the squeaking may be controlled. Ultra-High Molecular Weight Polyethylene (UHMWPE) as a prosthetic material is also a viscoelastic material [34]. Glaser et al. [35] indicated that C/C and M/M implants transfer more energy in the form of vibration to the surrounding tissue than C/P and M/P implants do, in which the energy is dissipated by the polyethylene insert. Therefore, UHMWPE is chosen as the damping in COC system prosthesis. In order to reveal the influence of damping on the vibrant stability of the ceramic hip endoprosthesis system, UHMWPE is chosen as a damping material in the present study and added to the acetabular component in three different schemes, which include a damping ring, half a damping layer and a whole damping layer as shown in Fig. 11.

Fig. 12 shows the unstable mode frequency distributions of the systems after adding UHMWPE damping material in the acetabular component. It can be seen that all of the unstable mode frequencies are close to those without damping in the baseline system. In order to have a better understanding of the vibrant stability of the system after adding UHMWPE damping material to the acetabular component, the mode coupling of the systems is studied as follows.

Fig. 13 shows the mode coupling of the system after adding UHMWPE damping material to the acetabular component. When adding a damping ring and half a damping layer to the acetabular component, the critical friction coefficients of mode(5, 6) and mode(7, 8) are nearly the same as those without damping in the baseline system. However when adding a whole damping layer in the acetabular component as shown in Fig. 13c, the critical friction coefficient of mode(5, 6) increases from 0.16 to 035. This result shows that the vibrant stability of ceramic hip endoprosthesis system is improved to a great extent. Compared with that with a damping ring in Fig. 13a and that with half a damping layer in Fig. 13b, the critical friction coefficient of mode(5, 6) with a whole damping layer in Fig. 13c is larger. It shows that adding a whole damping layer to the acetabular component can improve well the stability of the ceramic hip endoprosthesis system, therefore can suppress the squeaking.

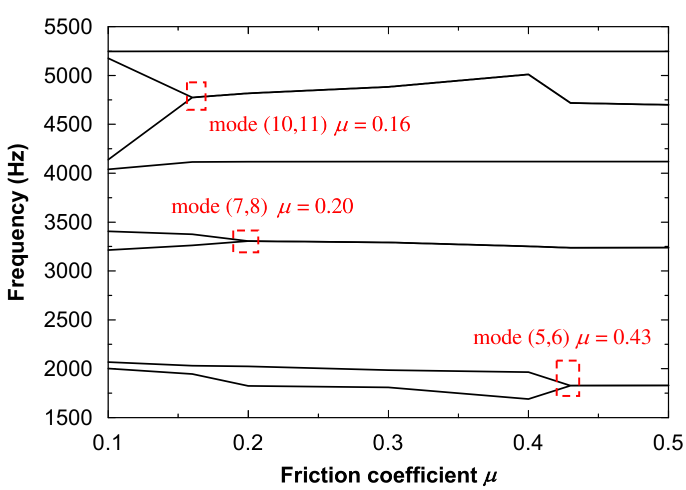

Fig. 10. Mode coupling of the ceramic hip endoprosthesis system after adding 316 L SS in the stem.

4. Discussion

The torsional vibration of the femoral component at 1843–2050 Hz and the flexural vibration of the femoral component at 3300 Hz are found be responsible for squeaking. Two methods including stiffening the stem and adding damping are proposed in the present study to improve the capacity of the ceramic hip prosthesis system to resist the torsional vibration and the flexural vibration of the femoral component. There are two ways to stiffening the stem. One is increasing Young's modulus of the stem, another is modifying the structure of the stem such as adding hard alloy to the stem. When Young's modulus of the stem is increased to $1.3E_0$, the critical friction coefficients of mode(5, 6), mode(7, 8) and mode(10, 11) increase from 0.16 to 0.17, from 0.2 to 0.23 and from 0.17 to 0.18, respectively. When CoCrMo alloy is added in the center of the stem, the critical friction coefficients of mode(5, 6) and mode(7, 8) increase from 0.16 to 0.43 and from 0.2 to 0.23, respectively. Compared these two ways, it can be easily found that increasing Young's modulus of the stem, the critical friction coefficients of the unstable modes just increase a little. It may theoretically control the squeaking to some extent, but may not work well in a real condition. While adding CoCrMo alloy in the center of the stem, the stability of the system be improved a lot. There is one thing, stress shielding, should also be taken into consideration since the stem should not be too stiff to prevent stress shielding. Therefore, more relevant experimental studies should to be done to find a practical way to add hard alloy to the stem. When a whole damping layer is added in the acetabular component, the critical friction coefficient of mode(5, 6) increases from 0.16 to 035. It indicates that a whole damping layer converts the mechanical energy resulting from the high friction between the liner and the ball into heat. While the damping ring and half a damping layer cannot. There is also a problem that more damping is added into the system, more wear debris from UHMWPE may produce. Therefore, lots of experiments in vivo and vitro need to be done in future.

Although the critical friction coefficient of the COC hip prosthesis system cannot increase to 0.5, the methods proposed in the present study provide research directions for suppressing squeaking. Of course, if the lubrication between the liner and the ball works well, the COC hip prosthesis system can never generate squeaking. Therefore, keeping a good lubrication condition between the liner and the ball is the most important way to suppress the squeaking. Understanding the motion behavior of the implant is the first thing should be done. In the present study the vibrant motion of the femoral component is revealed, while the motional behavior of the liner is not completely understand since the boundary conditions of the system is simplified to make the calculation is convergent. More relevant research work should be done in future.

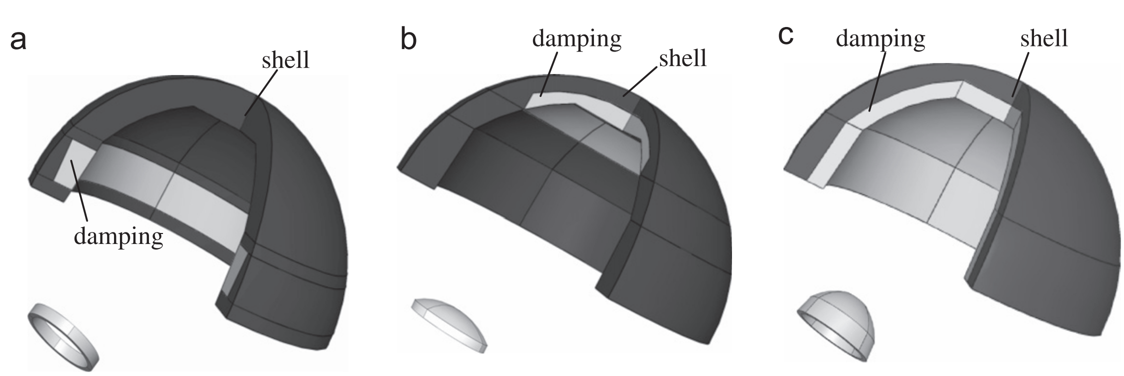

Fig. 11. Three schemes for adding damping to the acetabular part: (a) Damping ring, (b) half a damping layer and (c) whole damping layer.

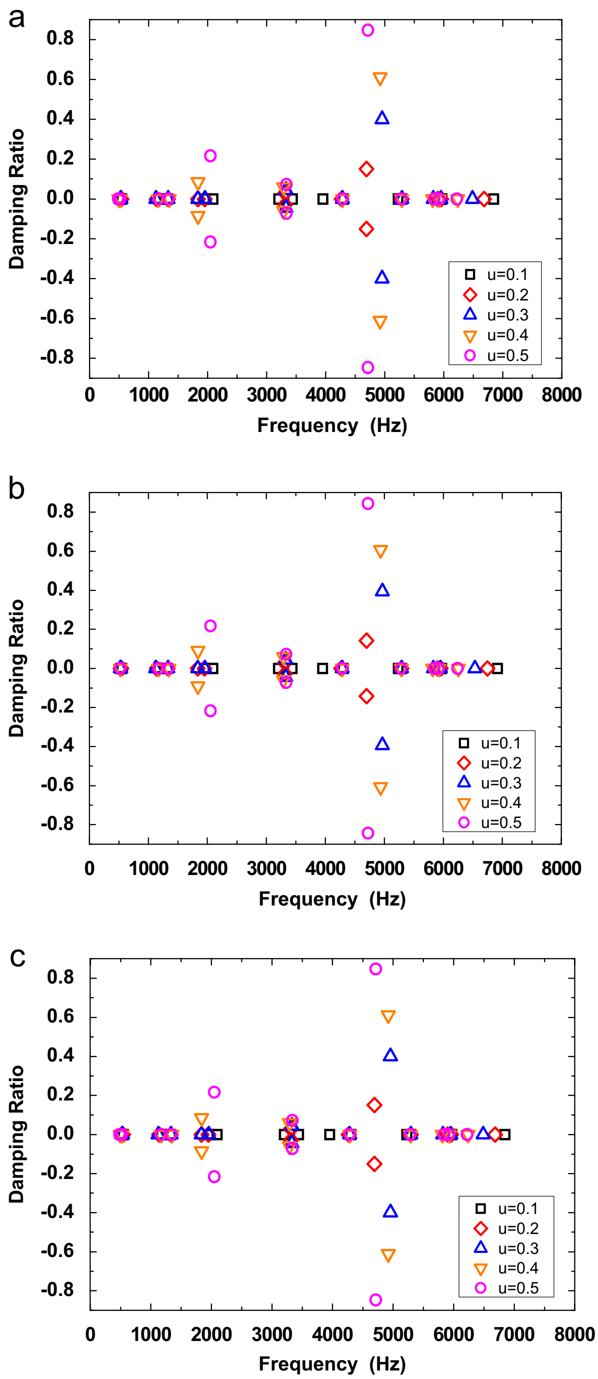

Fig. 12. Unstable mode frequency distribution of ceramic hip endoprosthesis systems after adding damping to the acetabular parts: (a) adding a damping ring, (b) adding half a damping layer and (c) adding a whole damping layer.

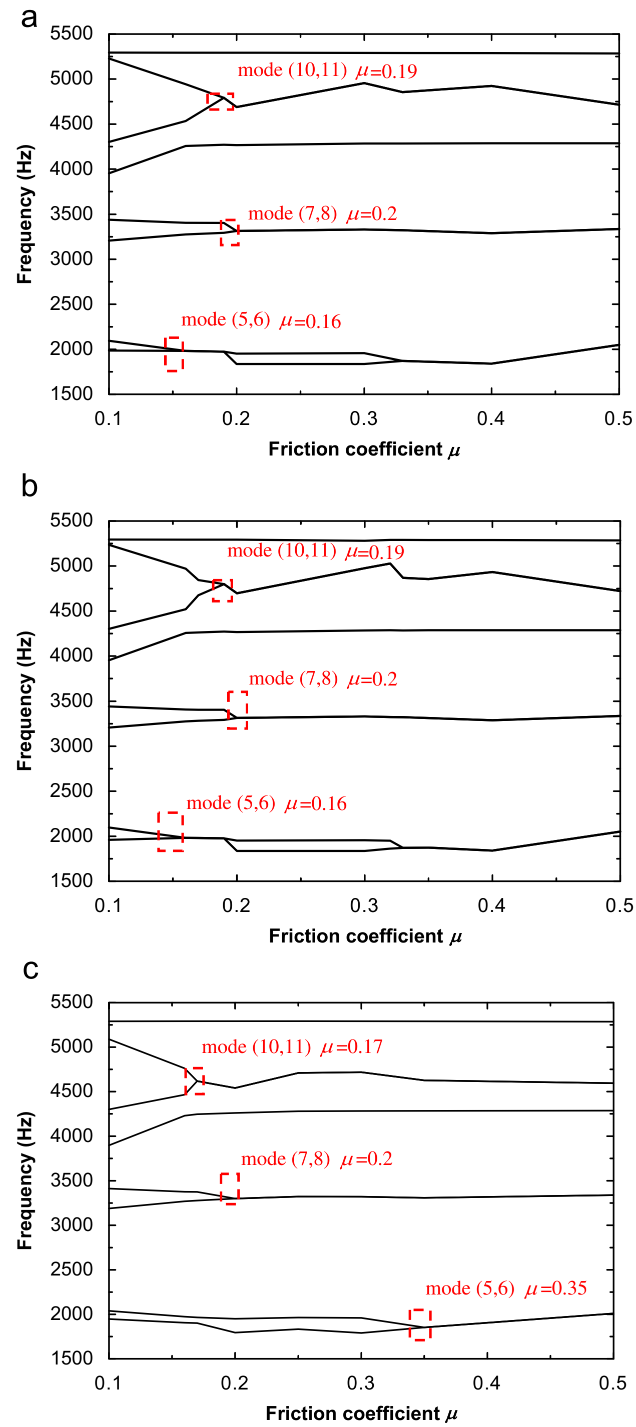

Fig. 13. Mode coupling of the ceramic hip endoprosthesis system after adding damping in the acetabular parts. (a) Mode coupling of the system after adding a damping ring, (b) mode coupling of the system after adding half a damping layer and (c) mode coupling of the system after adding a whole damping layer.

5. Conclusions and outlook

The finite element model of a ceramic hip endoprosthesis system is established using ABAQUS 6.7. The methods for suppressing squeaking are proposed according to a study of the vibrant stability of a ceramic hip endoprosthesis system under friction coupling. The present research work provides two research directions for suppressing squeaking. One is improving the capacity of the ceramic hip endoprosthesis system to resist unstable vibration of the femoral component, another is adding damping to the system to dissipate more energy resulting from one ceramic bearing rubbing against another ceramic bearing. The critical friction coefficients of the unstable modes including mode(5, 6) and mode(7, 8) of the system are proposed to judge the stability of COC hip endoprosthesis system. The detailed conclusions are summarized as follows:

(1) The stiffness of the stem has a great influence on the stability and squeaking generation of the COC prosthesis system. When Young's modulus of stem is decreased to 60–70% of the baseline, the critical friction coefficient of unstable mode is decreased to 0.05. The stability of the system decreases a lot

with a decrease of the stem's stiffness. Therefore, decreasing the stiffness of the stem leads to easier occurrence of squeaking. When Young's modulus of stem is 130% of the baseline, the critical friction coefficients of unstable modes increase a little. The stability of the system increase a little with an increase of the stem's stiffness. Therefore, increasing the stiffness of the stem may theoretically control the squeaking to some extent.

(2) Adding CoCrMo alloy and 316 L SS in the stem can improve the vibrant stability of the ceramic hip endoprosthesis system to a great extent, and adding CoCrMo alloy in the center of the stem is the best way to improve squeaking propensity of the ceramic hip endoprosthesis system since the critical friction coefficients of mode(5, 6) and mode(7, 8) increase from 0.16 to 0.43 and from 0.2 to 0.23, respectively.

(3) Damping has a large influence on the vibrant stability of the ceramic hip endoprosthesis system. Adding a whole damping layer to the acetabular component can improve the vibrant stability of the system. The whole damping layer has a better effect on suppressing squeaking propensity of the ceramic hip endoprosthesis system than the damping ring and half a damping layer do.

In the future, more experimental tests in vivo and in vitro studies of ceramic hips need to be carried out to validate the feasibility of the methods proposed for suppressing squeaking.

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